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Central mass accumulation in nuclear spirals

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Abstract. In central regions of non-axisymmetric galaxies high-resolution hydrodynamical simulations indicate spiral shocks, which are capable of transporting gas inwards. The efficiency of transport is lower at smaller radii, therefore instead of all gas dropping onto the galactic centre, a roughly uniform distribution of high-density gas develops in the gaseous nuclear spiral downstream from the shock, and the shear in gas is very low there. These are excellent conditions for star formation. This mechanism is likely to contribute to the process of (pseudo-) bulge formation.

1. Introduction

Galaxies with non-axisymmetric mass distribution induce efficient gas inflow, which can span throughout most of the galaxy, leading to the accumulation of gas in the galaxy centre, on scales comparable to the resolution limits of observations or computation. In some cases, high-resolution data indicate presence of nuclear rings in the innermost few hundred parsecs of a galaxy, where gas density is high and star formation occurs. Kormendy & Kennicutt (2004) postulated that stars created there eventually give rise to pseudobulges. Although formation of nuclear rings can be studied in detail with grid-based hydrodynamical modelling within the Eulerian scheme (e.g. Piner et al 1995), evolution of galaxies is most often studied within the Lagrangian scheme (e.g. SPH methods), which appears more flexible. However, these studies usually do not resolve the central gas concentration resulting from inflow (e.g. Di Matteo et al. 2007), usually called the central blob. SPH studies that resolve nuclear rings in some cases, in other cases still produce a central blob (Patsis & Athanassoula 2000). On the other hand, high-resolution Eulerian models indicate that aside for nuclear rings, nuclear spirals can form in centres of galaxies (Englmaier & Shlosman 2000, Maciejewski 2000, Maciejewski et al. 2002). Recently, most detailed studies within the Lagrangian scheme (Ann & Thakur 2005) demonstrated that the central blob can be resolved into a spiral, and is equivalent to nuclear spirals seen in the models built with the Eulerian scheme. In Maciejewski (2004b, hereafter M04b), I showed that nuclear ring and spiral are two modes of wave propagation in centres of galaxies. Here I focus on nuclear spirals, since nuclear rings have been already studied in detail.

2. Gas dynamics in nuclear spirals

Generation of nuclear spirals can be well explained within the framework of gas response to a fixed rotating stellar potential (Englmaier & Shlosman 2000). Gravity torques generate waves in gas that for any power-law rotation curve can propagate between the centre of the galaxy and the single Inner Lindblad Resonance present in that case (Maciejewski 2004a). The waves in this region give rise to a spiral morphology in gas with the pitch angle proportional to the velocity dispersion in gas. Centres of non-axisymmetric galaxies act as resonant cavities, and generation of waves is inevitable there.

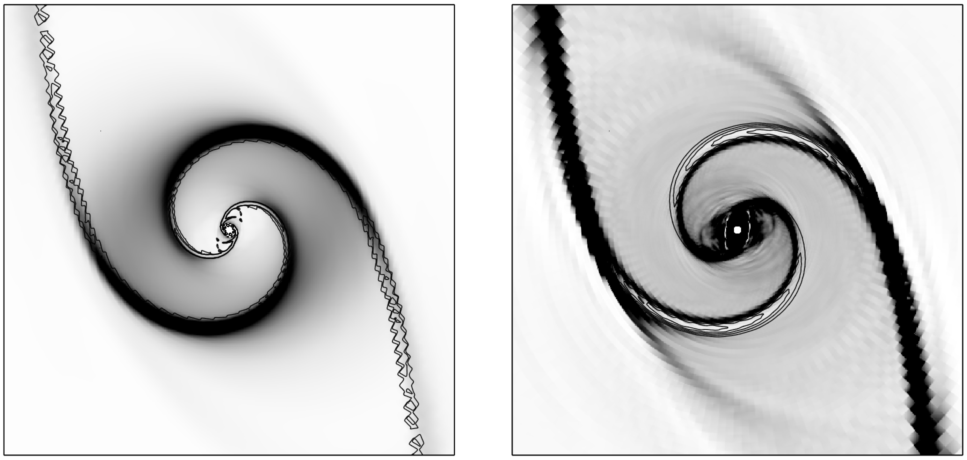

Figure 1. *Left:* A snapshot of gas density (greyscale) and $\mathrm{div}^2 v$ (contours; only for $\mathrm{div}v < 0$) in Model 8S20r of gas flow in a barred galaxy from M04b. Darker shading indicates higher density. *Right:* For the same model, S^2 (shear) is shown in greyscale, with the highest gas density overplotted in contours (unlike in the left panel). Darker shading indicates larger shear. The snapshot was taken at 0.5 Gyr, after the flow has stabilized. The bar is 6 kpc long and is vertical on the plots. The box is 2 kpc long.

In M04b, I studied nuclear spirals with grid-based models constructed within the Eulerian scheme. I showed that models for small departures from axial symmetry are in excellent agreement with the analytical solution, which provided an anchor for considering strongly barred models. Gas density and the location of shocks in nuclear spirals was given in M04b. Shocks were traced by large negative values of the divergence of gas velocity field. Divergence is a measure of expansion of the fluid, and its highly negative values should indicate gas compression in shocks. Here, I add one more characteristic of the flow: its shear. The measure of shear in the plane of the galactic disc should take a form $\partial v_x/\partial y + \partial v_y/\partial x$, but this form is not invariant under rotation of the coordinate system. However, shear can still be characterized by a single invariant value for a two-dimensional flow in a plane. This value can be derived from the stress tensor $A_{ij} = \partial v_i/\partial x_j$, after extracting its symmetric part, and leaving out the asymmetric one, responsible for the curl of the velocity field. Furthermore, the trace has to be separated out, since it solely contains terms corresponding to the expansion of the fluid, i.e. the divergence of the velocity field. As a result, one is left with the tensor $D_{ij} = (A_{ij} + A_{ji})/2 - A_{kk}\delta_{ij}/2$, which describes the shear of the flow only. This is a traceless, symmetric tensor. The measure of its magnitude can be obtained from its eigenvalues. In two dimensions, the two eigenvalues of a traceless tensor have opposite signs, but the same magnitude S, which describes the amplitude of shear, and is expressed by

$$S^2 = (\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x})^2 + (\frac{\partial v_x}{\partial x} - \frac{\partial v_y}{\partial y})^2.$$

Here I calculated the shear of gas velocity field in Model 8S20r from M04b, where the nuclear spiral is present. Fig.1 displays the gas density, square of divergence of the velocity field, $\mathrm{div}^2 v$, as the shock indicator, and S^2 as the indicator of the shear. Following the flow in Fig.1 from outside in, one can notice two almost straight lanes, with density slightly above average, and strong shock and shear. These lanes, almost vertical in Fig.1, mark the principal shocks in the bar that often manifest themselves as a pair of straight

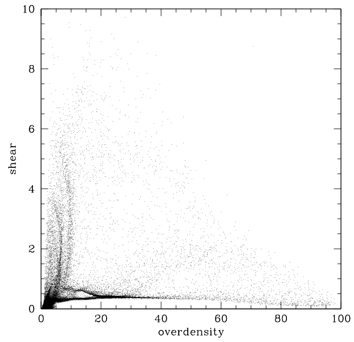

Figure 2. Shear as a function of overdensity for 512^2 elements of the model from Fig.1.

dust lanes. As expected, the highest density in gas is located downstream from the shock (gas rotates counterclockwise in Fig.1), and high shear extends downstream from the shock as well. When the flow is followed inwards, the principal straight shock takes a spiral morphology, which I call the nuclear spiral (see also Englmaier & Shlosman 2000, Maciejewski et al. 2002, M04b). The divergence of gas velocity field remains highly negative, which indicates that the nuclear spiral is a shock in gas. The highest density in gas is still downstream from the shock, as expected.

On the other hand, the distribution of shear in gas in the region of the nuclear spiral is more complicated and very interesting. As the principal shock curves inwards and turns into the nuclear spiral, at azimuthal angles somewhere half-way between the minor and the major axis of the bar, the thick dark lane marking large shear in the right-hand panel of Fig.1 splits. One branch is exactly co-spatial with the shock – this indicates large shear in the nuclear spiral shock. The other branch curves less than the spiral, splits again, and disappears around the major axis of the bar. Between these two branches of high shear, there is a pocket of the lowest shear in the region, immediately downstream from the nuclear spiral shock, and exactly co-spatial with the post-shock gas of highest density. Thus the high-density post-shock gas that forms the gaseous nuclear spiral experiences very little shear, contrary to the post-shock gas in the straight shock in the bar. This difference becomes clear once the region presented in Fig.1 is divided into elements, and for these elements the shear, quantified by S^2, is plotted against overdensity, i.e. the ratio of the measured density to the initial one in the model, as in Fig.2. The points in the plot group in two perpendicular stripes: the vertical one, with overdensity about 10 and high shear, and the horizontal one, with low shear, below 0.5, but highest overdensities, reaching 100. It can be shown that the vertical stripe contains gas emerging from the straight shock in the bar, while the post-shock gas in the nuclear spiral groups in the horizontal stripe.

3. Conditions for star formation

Presence of shocks and shear influences star formation: shocks trigger the collapse of molecular clouds, while shear may destroy the clouds. Thus one should expect enhanced star formation in the presence of shocks, but this may be inhibited by strong shear. In Model 8S20r, analyzed above, gas orbiting around the galaxy centre passes through the nuclear spiral shock roughly every 10 Myr. Immediately downstream from the shock, it is compressed in gaseous spiral arms, whose density is a few times higher than the inter-arm density, and where shear is negligible. These are excellent conditions for star formation.

Therefore in nuclear spirals star formation should occur on much higher rate than in the case when the inflowing gas gathers in an amorphous blob, which lacks shocks and post-shock high-density low-shear gas. Note however that star formation should not be confined to the gaseous spiral arms. Its timescale is of the order of crossing time between the arms (10 Myr), and one should expect that only the first step of star formation, the formation of self-gravitating cores, occurs in the arms. However, young stars should appear at any azimuthal angle. Therefore, although star formation is triggered by the spiral shock, it is distributed in a disc or wide ring.

The dynamics of nuclear spirals presented here is determined only by gas response to an external gravitational potential. This process is well understood and its workings can be studied in detail. Obviously, self-gravity in gas, and feedback from star formation will make the picture presented here more complicated. However, once these processes are included, results become uncertain, as star formation is poorly understood. Since in nuclear spirals compression of gas is induced by the spiral shock, the role of self-gravity in gas may not be dominant there. Also the feedback from star formation is likely to be weakened by the fact that most of the stars are not formed in the dense gaseous nuclear spiral.

4. Conclusions

I presented here the mechanism of central mass accumulation in nuclear spirals. When a nuclear spiral is present in the centre of a galaxy, gas passes through the nuclear spiral shock every 10 Myr or so, with no shear in the post-shock compressed gas. This reoccurring condition for star formation makes something like a cycle engine that efficiently converts gas into stars in the galaxy centre. Stars are also formed in nuclear rings, but the distribution of material accumulated in nuclear spirals is more bulge-like, since the spiral spans over a considerable radial range. Star formation rate in nuclear spiral is likely to be higher than in nuclear ring, since the nuclear spiral shock accompanies the gaseous spiral throughout its extent, while the nuclear ring damps the shock (see M04b). Nuclear spirals might have played a crucial role in the early Universe, since they form in gas with high velocity dispersion, likely present in newly formed galaxies. Ann (2005) also showed that nuclear spirals form preferably in less massive galaxies. Like nuclear rings, nuclear spirals may be responsible for the formation of pseudobulges, or, as it was pointed out during this meeting, disky bulges, since we still do not know how to lift gas or stars from the galactic plane.

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